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The Effect of Drilling Fluid Rheological Properties on Hole Cleaning

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Abstract

Hole cleaning is still among the most important problems to handle in drilling operations. The difficulty in removing cuttings bed during drilling arises because of the drilling fluid interacts with the cuttings in cuttings bed to form a cuttings bed gel. The drilling fluid composition can be designed to minimize the gel formation in the cuttings bed. At the same time the drilling fluid properties are optimized to ensure a sufficient shear stress on the cuttings particles to be able to remove the cuttings. This technique has been used in several of Statoil's drilling operations.

The paper explains the effect of the cuttings bed properties on hole cleaning in detail. Furthermore, the paper demonstrates how the drilling operations were improved compared to earlier drilling operations using conventional drilling fluids. From drilling operations in North Sea fields it is shown how the total drilling progress is improved. The torque curves of comparable wells are shown. These curves demonstrate that a significantly improved hole cleaning have been experienced in the wells drilled with the drilling fluid made to minimize cuttings bed gel formation.

Introduction

Although large resources have been spent on studying hole cleaning, there is still a debate going on how to optimize hole cleaning properties. The necessity of understanding hole cleaning is caused by the different operational problems that can arise if sufficient hole cleaning is not achieved. Poor hole cleaning may result in lost circulation or hinder the casing or liner to be run into its selected position. Therefore, it is important to use the correct operational practice to ensure optimum hole cleaning. Presently, recommendations to obtain

good hole cleaning vary, depending on the different experiences or other sources that the recommendation is based.

Recently, it has been recognized that the cuttings bed consolidation properties are important in evaluating the potential for hole cleaning¹. Although these properties has not been fully implemented in practical evaluation during the drilling operation, the properties have been used indirectly in modeling hole cleaning ability through the use of necessary shear stress at the cuttings bed surface to remove cuttings².

Oil based and water based drilling fluids have been found to act differently in respect to hole cleaning even though their viscosity profiles may have been fairly equal. The different behavior is caused by the different ways these drilling fluids are constructed. Oil based drilling fluids are formulated using a continuous oil phase. The oil based drilling fluids are viscosified by the addition of emulsified water, typically in concentrations between 15 and 25% and by the addition of organophilic clay. There is no contact between the cuttings and the water when drilling with oil based drilling fluids.

In water based drilling fluids a brine phase is viscosified by different polymers. These polymers will couple the fluid to the cuttings and thereby create a possibility for the fluid to generate a more or less consolidated cuttings bed.

In the present paper there is an evaluation of the effect of the drilling fluid rheological properties of water based drilling fluids on hole cleaning properties in deviated wells. Although the effects on the cuttings bed are different when oil based drilling fluids are used, there are a few conclusions that can be generalized from the water based drilling fluid case to also be valid for drilling with oil based drilling fluids. These generalizations are also summarized in the article.

The evaluation presented in the present article is based on results from several wells from different fields in the North Sea. In these wells the well paths include most sections from the more problematic 45°-70° deviations to horizontal sections where saltation flow could help simplifying hole cleaning. It is recognized from investigations that drill pipe rotation has positive effects on hole cleaning³. In practical operations, drill pipe rotation is well known to give better hole cleaning.

Effect of cuttings bed properties on hole cleaning

The cuttings bed properties have a major influence on hole cleaning¹. If the cuttings bed is loose and porous, it is only necessary to remove single cuttings particles that are not

adhered to the bed. In this case it will be easy to remove the bed. In the opposite case, if the cuttings bed is well consolidated no cuttings particles are free to be removed alone from the bed by the flow, hole cleaning is difficult.

Generally, it is desirable to minimize the cuttings bed consolidation as much as possible. Some fluid may migrate through a loose and porous cuttings bed⁴. In theory, this fluid migration can reduce the flow above the bed. This migration flow, however, is not expected to be significantly large in practical operations and should not hinder hole cleaning, which will be optimized when the bed is as loosely consolidated as possible. On the contrary, this flow may help keeping the cuttings bed loose.

Effects of drill pipe rotation on hole cleaning

Drill pipe rotation may add a complexity to the picture described in the previous paragraph slightly. It has been suggested that removal of the cuttings bed is simplified in the presence of drill pipe rotation when drilling with viscoelastic drilling fluids⁵. A semi-consolidated bed can in some, albeit rare cases be removed because the drill pipe drags a large portion of the bed around from the bottom of the annulus to the top were the high flow rate is. The high flow rate can then disperse the removed cuttings to some degree and good hole cleaning may be achieved. This behavior is particularly a possibility for removing sand beds and other non-reactive cuttings particles.

The flow of a fluid between a rotating drill pipe and the formation or cased wall is seldom stable. The flow is vulnerable for Taylor vortices. These vortices add to the flow like a weak turbulence even in absence of flow⁶. For low viscosity fluids these vortices were known already in 1880⁷. When these Taylor vortices appear, the flow acts like turbulent to some degree. The turbulence like motion makes the frictional pressure loss to increase, resulting in an increased shear stress on the cuttings bed surface. This increased shear stress will finally assist in removing more cuttings⁸.

Positioning of the drill pipe in the center of the well bore is unlikely. In eccentric cases the frictional pressure loss and thereby the ability to remove cuttings is increased by another effect. The drill pipe motion move fast flowing fluid from the wide part of the well bore down into narrow sections sandwiched between the formation and the drill pipe. In these narrow regions the flow feels strongly the presence of the walls and the flow is retarded. The fluid originally flowing in these narrow areas are forced to move to the wide areas where the velocity is large. Therefore, these slowly moving fluid volumes in the narrow areas are forced to accelerate. These alternating accelerations and retardations easily create an increase in annular pressure losses even though Taylor vortices may not have been formed⁹.

In practical operations, Taylor vortices would be present even at a drill pipe rotation rates far below 60 rpm¹⁰. Taylor vortices can easily be formed at rotation rates in the magnitude of 20-30 rpm for certain fluids. The larger the rotation rate is, the more turbulence like the motion becomes and the frictional

pressure losses increase. Therefore, the optimum hole cleaning condition should be using as high drill pipe rotation rate as possible.

Controlling the cuttings bed properties

When drilling with water based drilling fluids there is a danger that water can react with the cuttings to form a gel type bonding between the different cuttings particles. Any type of gel formation in the drilling fluid itself will increase the tendency of particle bonding. If this particle-particle bonding is strong, there is a need for a large force on the cuttings bed surface to be able to remove the cuttings. Therefore, to optimize hole cleaning, it is desirable to reduce both the initial and the long time formed gel strengths as much as possible. In practical operations this means that both the 10 seconds and the 10 minutes gel strength should be as low as possible to obtain proper hole cleaning.

Controlling the gel strength of the drilling fluid is insufficient to obtain cuttings bed properties benign for hole cleaning. Other important parameters are the viscoelastic properties of the drilling fluid. It is important that the formed gel cannot resist a large strain. The smaller strain that is necessary to break the gel, the better. Typical additives that will create strain resistive gels are long polymers that are difficult to shear degrade or long multiple bend type polymers, which creates large elastic effects in small concentrations. An example of the first type of polymer is Xanthan gum and an example of the long multiple bend polymers are high molecular weight partly hydrolyzed polyacrylamides dissolved in fresh water.

In practical operations, it is desirable not to viscosify the drilling fluid by the addition of Xanthan gum polymers or similar products. These additives should only be used in concentrations necessary to control the barite sag potential within accepted limits. Any further viscosification should be performed using low molecular weight polymers like carboxyl methyl celluloses (CMCs) or polyanionic celluloses (PACs).

A practical way of creating drilling fluids with a limited degree of gel formation is to use thin fluids. The fluids should be thin within the realistic shear rate range. This shear rate range spans 0 – 200 inverse seconds, approximately, or 0 – 100 rpm on a VG-meter.

If large concentrations of high molecular weight polymers like the Xanthan gum are present, the fluid will exhibit a significant drag reduction. This drag reduction result in a lower shear stress onto the cuttings bed surface and a poorer hole cleaning. This drag reduction argument is an additional argument stating that the Xanthan gum concentration should be as low as possible in water based drilling fluids.

If water based drilling fluids exhibit a large degree of shear thinning, a cuttings bed surface will be exposed to a lesser shear stress than would be the case if a lesser shear thinning fluid is used. In this case, with significant shear thinning, hole cleaning can be difficult in periods with long steering periods. Furthermore, products giving the high degree of shear thinning will naturally produce a large degree of consolidation of the

cuttings bed. Therefore, it is ideal to use drilling fluids with a low shear dependency of the viscosity, like for example Newtonian fluids.

When the drilling fluid viscosity and gel strength become very low, the potential for barite sag will increase. Therefore, it is essential that barite sag is given full attention during the drilling operation with thin drilling fluids.

A positive side effect of using thin drilling fluids with insignificant gel formation is that all types of solids control equipment will function better.

Evaluation based on experience

Current field application

Thin fluids with only a limited gel formation has been applied on several fields offshore Norway. In the first example the drilling progress will be compared for 28 wells spanning a time period from 1996 to late 2001. The drilling progress observed at this field is shown in Fig. 1. This figure show the drilling rate calculated as the total well section depths divided by the total time from start of the 17 1/2" section to finishing drilling the 8 1/2" section. The total time includes the time spent on back reaming, washing, circulating and running casing. Before well number 12, the wells were drilled with more viscous drilling fluids. These drilling fluids were viscosified primarily by the use of Xanthan biopolymers.

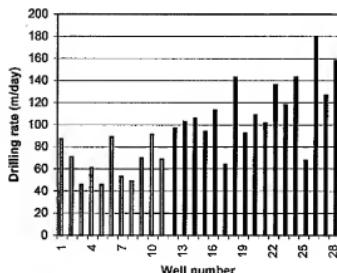


Fig. 1. - Average total drilling rate for the whole well. Well numbers are in chronological order. Black bars refer to wells with implemented hole cleaning theory.

From well 12, shown in Fig. 1, and onwards only low viscosity drilling fluids were used. These were viscosified with biopolymers only to minimize sag of barite. Further viscosification was primarily done by the addition of PACs. Typical changes in viscous properties are illustrated by the data shown in Table 1. This table shows the VG-meter dial readings for well number 4 and well number 26. As can be seen from the data, the fluids used in the latter wells, from

well number 12 and onwards, have been significantly thinner for the typical shear rates observed in the annulus while drilling. Furthermore, the gel formation has been significantly reduced. This gel strength reduction is important to optimize hole cleaning.

As can be easily seen in the data shown in Fig. 1, there has been a significant improvement in the drilling speed from well 12 and onwards where the new thin drilling fluid was used. The defined as total drilling length divided by time spent from the start of drilling the first section to delivering the well to completion after drilling the last section. There is an immediate increase in drilling speed from well number 12. In this particular field, a significant effort was spent on increasing the drilling rate. One of the solutions was to change the viscous properties of the drilling fluid. Other drilling changes were implemented. However, some of these changes have been changed back into the original methods, leaving the change in viscosity as one of the more definite changes.

The improvement in drilling rate from avoiding hole stability problems by selecting the optimum concentration of KCl^{11} has not been fully applied on this field yet. A substantial fall back in drilling rate to the older drilling rates was observed in well 17. However, in this well insufficient precautions had been taken to avoid sag; producing severe well problems. Taking these problems into account this well should not be used in the analysis of the thin drilling fluid for optimizing hole cleaning.

The drilling rate of well number 25 is also comparable with the drilling rates of the wells drilled with more typical viscosity values of the drilling fluid. This well, however, was only a side track in an 8 1/2" section where the drilling speed had to be low for other reasons, and should not be used for evaluating the hole cleaning properties.

Table 1. - Typical viscosity values and gel tests for the drilling fluids used in wells 4 and 26 referring to Fig. 1.

VG-meter rpm and gel data	Well number 4	Well number 26
600	99	56
300	69	36
200	57	29
100	41	18
60	33	14
30	24	9
6	14	3
3	10	2
10 s gel	6 Pa	1 Pa
10 min gel	16 Pa	2 Pa

When drilling with thin drilling fluids there is always a danger that the wear on the equipment will increase. The lifetime of wear exposed parts of the measurement while drilling (MWD) tools in the wells shown in Fig. 1 have been altered by the introduction of thinner drilling fluids. These parts in the MWD are normally being used on several runs.

Typical data for this particular field is that the lifetime of these parts has been reduced to somewhere around the half of the earlier lifetime. An increase of the wear on the drillpipe has also been observed. Still, the value of the increased drilling rate resulting from improved hole cleaning is higher than the increased cost resulting from increased equipment wear.

A similar hole cleaning philosophy has also been used on another field with success. In this case the fluid viscosity curves demonstrated values between the conventional values and the values seen at the first field. For this particular field, no hole cleaning problems have been reported. However, as was the case for the first field, there had been a significant wear on the MWD valves¹².

Sidetrack comparison

The drilling of a 17 1/2" section in a field where the well had to be sidetracked twice because of equipment failure, clearly illustrates the importance of keeping the viscosity and gel formation values as low as possible. In this case three comparable sections with nearly identical well paths were drilled, giving data, which is applied in the analysis of hole cleaning properties. Typical viscosity and gel formation data for this particular well is shown in Table 2. The drilling fluids used in both Track 1 and 2 can be considered as thin. The viscosity values are comparable for shear rates less than 100 rpm on the VG-meter, corresponding to shear rates less than 170s⁻¹. The viscosity for shear rates above 170s⁻¹ is higher in Track 1 than in Track 2. However, in the annulus, near the cuttings bed, the flow is seldom exposed to such high shear rates. More important, it can be seen from the data shown in Table 2 that the gel formation in the fluids used in Track 1 and Track 2 is insignificant compared to the gel formation in the fluid used in Track 3.

Table 2. - Typical viscosity values and gel tests values for the drilling fluids used in the sidetrack comparison.

VG-meter rpm and gel data	Track 1	Track 2	Track 3
600	71	52	97
300	40	30	65
200	30	21	56
100	19	17	43
60	12	11	36
30	8	6	29
6	3	2	15
3	2	1	12
10 s gel	1 Pa	1 Pa	8 Pa
10 min gel	2 Pa	2 Pa	15 Pa

The drill string torque data for the tracks used in the comparison is shown in Fig. 2. In this figure it is shown the average torque on the drill string measured as a function of depth. It is easily seen from the data for Tracks 1 and 2 that the torque readings are significantly less than the torque readings for Track 3.

The flow rate was comparable, although different, for all the tracks: 4300 l/minute in Track 1, 4500 l/minute in Track 2 and 4450 l/minute in Track 3. The lowest torque reading was observed in Track 2. The difference in the torque observed in Tracks 1 and 2 is probably because of the small difference in flow rate in these two tracks. The increased flow rate in Track 2 compared to Track 1 probably improved hole cleaning further, resulting in a cleaner hole and a lower torque.

There is a significant reduction in the drill string torque in Track 3 at 2908m depth. In this case the bit was tripped out of the hole. The well was cleaned during tripping out. When drilling started after tripping in, the drill string torque was equivalent to the torque observed in Track 1. This torque indicates that the hole was clean and in equal conditions to the hole in Track 1.

When drilling continued in Track 3 after the tripping, the torque values resumed the values before the tripping. This indicates that the cuttings bed had been reformed. Furthermore, it should be noted that at this point lubricants were added to reduce the drilling string torque. This operation was not successful, indicating that lubricating the drill string is not a good practice when the torque is caused by poor hole cleaning.

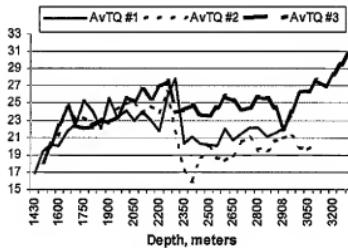


Fig. 2. - Drill string torque values as a function of depth measured in the three different well tracks

A clear conclusion from the sidetrack comparison is that less cuttings volume was left in the hole when the thinnest drilling fluid was used. In this case the drill string torque values were smallest indicating a lesser degree of tight hole resulting from the absence of cuttings left in the hole. At the same time the drilling rate, drill string pulling speed was highest indicating good hole cleaning.

Consequences for drilling with oil based drilling fluids

Real gels do not form generally in oil based drilling fluids. Still, there is a large degree of thixotropy in the drilling fluid.

Within practical terms, the fluids can be considered as having a yield stress. The presence of a fluid with a yield stress within the cuttings bed should have detrimental effects on hole cleaning. This idea contradicts the observed results where use of oil based drilling fluids normally optimizes hole cleaning.

The reason for this improved hole cleaning when using oil based drilling fluids is that there is no longer any cuttings particle-particle gel forming effect, since oil is the continuous phase which is inert on the particle surface. Furthermore, there are no elastic properties of the oil based drilling fluid that can be active in case of a non-infinitesimal strain. The result from these two effects is that the cuttings bed does not develop into a gelled bed structure the same way as a bed in a water based drilling fluid. Therefore, it will be easier to remove cuttings using oil based drilling fluid. A direct comparison between hole cleaning when using oil based and water based drilling fluids cannot be done.

If oil based drilling fluid is used, the same arguments than when using water based drilling fluids can be applied. This has been indicated from drilling operations with relatively thin oil based drilling fluids used in the second field. Optimum hole cleaning is achieved when the yield stress is as low as possible and when the API gel strength values are as low as possible. The danger of increased wear is increased, however, not as much as when drilling with water based drilling fluid¹².

The oil based drilling fluid viscosity cannot be as low as the viscosity observed in water based drilling fluids. Such very low yield stresses or very low API gel strength formation in oil based drilling fluids make these fluids more vulnerable for barite sag than does water based drilling fluids.

Conclusion

Field practice with water based drilling fluids based on hole cleaning theory and an evaluation of hole cleaning using comparable wells has verified the following major points:

- The drilling fluid gel formed in the cuttings bed is the primary cause of hole cleaning problems.
- Hole cleaning is optimized by the use drilling fluids with low gel strengths and with low viscosity within the shear rates exposed to in the annular flow.
- High molecular weight polymers should only be used for preventing barite sag. Further viscosification should be done using shorter polymers. This must be done to avoid creation of a strong cuttings bed gel.
- Use of drilling fluids demonstrating only a low degree of shear thinning give better hole cleaning characteristics than fluids demonstrating a high degree of shear thinning.

The evaluation has also identified that selecting drilling fluids with good hole cleaning characteristics may result in an increased wear on MWD equipment and drill pipes because of the low viscosity. The drilling fluid can also be more vulnerable for barite sag.

A positive side effect of using drilling fluids with low viscosity and low gel strengths is that the solids control equipment function is improved.

The rheology guidelines for selecting drilling fluids with good hole cleaning properties is similar when drilling with oil based drilling fluids. Gel strength readings should be as low as possible. The hole cleaning properties of oil based drilling fluids cannot, however, be compared directly with hole cleaning properties of water based drilling fluids.

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